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Application of compressible multi-component flow in underwater explosion problems

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Abstract

High-order accurate shock-capturing schemes had been proposed to resolve compressible flow movement that involving shockwave problem in single-fluid Riemann problems previously. However, when different fluids appear, oscillations often generate at the multi-component interfaces without deep implementations. An underwater explosion (UNDEX) event is typical multi-component problem with different flows phase evolvement. In order to simulate underwater explosion, we extend the numerical schemes which include five-order WENO reconstruction and HLLC approximate Riemann solver to capture interface between the explosive gas and water. Our method is high-order accurate, quasi-conservative and interface-capturing, which has been verified by 2D problems, and produce good agreement between analytical solution and experiment result. At last we attempted to use the method to simulate shock wave loading and underwater explosion (UNDEX) near a free surface

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Keywords: Multi-component flows; Underwater explosion; Interface capturing; WENO; HLLC solver

1. Introduction

High-order accurate shock-capturing schemes have been widely used in computational fluid dynamics to resolve compressible flow features. The finite difference and finite volume weighted essentially non-oscillatory WENO) [1-3] performs well in single-fluid problems. In early algorithms for computing compressible multi-component flows, the interface position is usually captured by the mass fraction volume of fluid (VOF) or level set method. The syetem equation is solved by second order accurate reconstructions with a Roe or HLL solver [4-5]. But Abgral[6]

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found that spurious oscillations easily appeared at interface and proposed a quasi- conservative method based on the mass fraction formulation for gases; subsequently, this method is extended the method to other general equation of state and multi-component flows[7]. Our goal is to simulate multi-component flow problems to avoid spurious oscillations near shockwaves and interfaces. In order to achieve this object, we have extended the interface capturing methods by implementing a high-order accurate WENO reconstruction and HLLC solver [8]. This system for multi-component flows and its discretization are showed in Section 2. In Section 3 the method is validated by several typical cases. Finally we apply our method to simulate underwater explosion near free surface.

2. Mathematical model description

2.1 Governing equation

In this work, both compressible gas and liquid flow are encountered. For the gas flow, gases are assumed ideal and inviscid Euler equation is employed. Both explosion gas and water are assumed to be compressible. So we can write the system for a 2D arrangement in a consistent form[9]:

$$\frac{\partial Q}{\partial t}+\frac{\partial F(Q)}{\partial z}+\frac{\partial G(Q)}{\partial r}=S(Q) \tag{2.1}$$

Here the respective expressions of Q,F,G,S and S for flows are given as flexes, ρ is the fluid density, u and v are the flow velocities in z and r directions, respectively, p is the pressure and E is the total energy per unit volume and given by $E=\rho e+0.5\rho\left(u^2+v^2\right)$, e the internal energy per unit mass. n is a system parameter which takes on a value of 1 or 2. To close the system, we use the stiffened equation of state [10].

$$p=(\gamma-1)\rho e-\gamma p_\infty \tag{2.2}$$

For perfect gases, γ is the ratio of specific heats and $p_\infty=0$; for water, $\gamma=5.5, p_\infty=0$ [16].

The interface between two flows is showed by the discontinuity in the properties, γ and p_∞ .of the different fluid components. Since material interfaces ware advected by the flow, the properties must obey the advection equation [12].

$$\phi_t+u\phi_x+v\phi_y=0\ ,\phi=\left\{\frac{1}{\gamma\text{-}1},\frac{\gamma p_\infty}{\gamma\text{-}1}\right\} \tag{2.3}$$

Equations (2.1)and(2.3) form the system governing equations. Equation (2.1) is conservative, while the advection equation (4) is non-conservative. So the system governing equations are quasi-conservative.

2.2 Spatial discretization

In multi-component flow simulation, finite volume(FV) method must be used to suppress oscillations generated at interface[12]. In computational cell $I_{i,j}=\left[x_{i-1/2},x_{i+1/2}\right]\times\left[y_{j-1/2},y_{j+1/2}\right]$, eqs(2.1) can be written in semi-discrete forms,

$$\frac{d\bar{\bar{q}}_{ij}(t)}{dt}=-\frac{\hat{f}_{i+1/2,j}-\hat{f}_{i-1/2,j}}{\Delta x_i}-\frac{\hat{g}_{i,j+1/2}-\hat{g}_{i,j-1/2}}{\Delta y_j} \tag{2.4}$$

where *q* approximates the c conserved variables and *f* and *g* approximate the fluxes in x,y direction respectively. In the FV formulation, the left and right states of Riemann problem are reconstructed from the cell averages in a piecewise constant fashion. ENO reconstruction chooses the optimal stencil to build the cell average value of a function, and the function is interpolated on either side of the cell edges. This method provides high-order accuracy and essentially non-oscillatory (ENO) scheme, While WENO reconstruction provides a convex combination of all the candidate stencils, and constitutes an improvement on ENO schemes on many levels. So in this paper we choose five-order WENO reconstruction scheme. Since two one-dimensional reconstructions are needed per grid point, a two-dimensional FV reconstruction is computationally intensive. In this situation, a Gaussian quadrature rule is used [13].

2.3 Spatial discretization

A s been said in Section 2.2, in FV formulation the physic fluxes are built on the approximate Riemann solver, which may use high-order reconstruction values. The approximate Riemann solver proposed by Harten Lax and van Leer(HLL) [5] requires estimates for the fastest signal velocities emerging from the initial discontinuity at the interface. In 1992 the HLLC Riemann solver was proposed. It is a modification of the HLL scheme, whereby the missing contact and shear waves in the Euler equations are restored. Meanwhile the HLLC resolves discontinuities sharply, and isolate shockwaves and contact exactly [12].In the condition of proper left and right states around the contact boundary, the HLLC solvers could preserve positivity. Expect for spatial discretization, the time-marching is used by third-order TVD Runge-Kutta schemes[1-2].

3. Results and discussions

3.1. Two-dimensional interaction of shock and air/helium bubble

This case is the collapse of an cylindrical helium cavity in air tube by a Mach 1.25 shock. This problem has been studied in experiment by Haas [14] due to its importance in a wide range of physical and practical phenomena. The rectangular computational domain for this problem is $\Omega=[0,0.325]\times[0,0.0445]$, and the two-dimensional symmetrical axis is y=0.0 An cylindrical helium bubble of 45mm radius is placed in air with its center at (0.175,0) , and the shock wave is initiated at $x=0.2$ at $t=0$ .The schematic of domain is shown in Fig.1. In calculating only up half part of the domain is needed. The rectangular computational domain Ω is discretized using a 650×88 uniform grid, with reflecting boundary conditions on the top and along the centerline.4

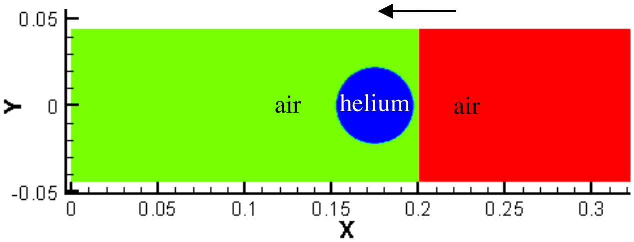

Fig.1 Schematic of the shock and Helium bubble in air

The test of the initial condition is

$$(\rho,u,v,p)=\begin{cases}(1.3764,-124.824,0,1.5698e5) & \text{after wave}\\(1,0,0,1.0e5) & \text{before wave}\\(0.138,0,0,1.0e5) & \text{in bubble}\end{cases} \quad (3.1)$$

where the specific heat ratio of air and helium are $\gamma_1=1.4$,and $\gamma_1=1.67$, respectively. The flow field at various times are shown in Fig.2.The computed solution shows good agreement between the simulation and experiment results.

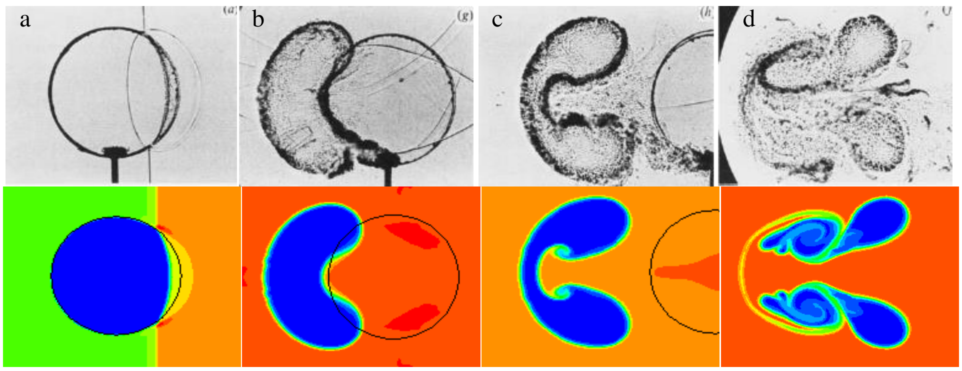

Fig.2 Shock and air/helium bubble interaction. Top: shadow-photographs of Haas and Sturtevant(1987), bottom: Numerical Schlieren-type results at (a)t=32μs, (b) t=245μs, (c) t=427μs, (d) t=983μs

3.2. Underwater explosion near a free surface

The problem of underwater explosion near a free surface has been simulated by [15-16] as a typical phenomenon in multi-component flow simulation. The initial conditions are given as follows: a highly pressurized explosion gas cylinder of 0.12 unite radius is located at the origin (0,-0.3) in water. The free surface is located at the straight-line y=0. The schematic of domain is shown in Fig.9. The initial condition is [15]

$$(\rho,u,v,p)=\begin{cases}(1.25,0,0,1.0e4) & for\ \ gas\\(1.225e\text{-}3,0,0,1.01325) & for\ \ air\\(1.0,0,0,1.01325) & for\ \ water\end{cases} \tag{3.2}$$

For this two-dimensional planer problem, The rectangular computational domain is [-2,2]×[-1.5,1.5], using a 600×450 uniform grid. The reflecting boundary conditions is put on the bottom, while the other direction boundary conditions are non-reflecting condition.

Fig. 3 Schematic of the underwater explosion near a free surface

The computing solution is listed in Fig.4. It depicts the flow field at different times between paper [16]and this paper's method. In pape [16], Shukla chose the five-equation model as the system governing equations, and the advected variables is volume of fraction of the gas. The results depicted in Fig.4 show good agreement between the two schemes.

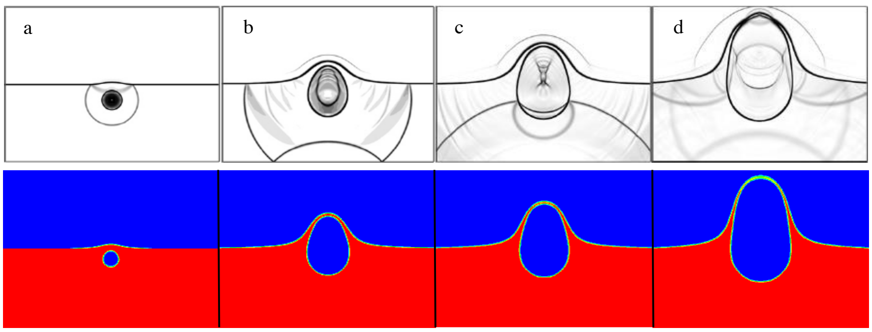

Fig. 4 Underwater explosion near a free surface. Up: numerical schlieren of Shukla(2010).Down: density contours at: (a)t=00.6, (b) t=0.25, (c) t=0.4, (d) t=0.6

4. Conclusions

In this paper, an accurate quasi-conservative scheme for simulating the compressible multi-component flows is proposed by five-order WENO reconstruction and HLLC approximate Riemann solver. This method has been tested by 2D problem, and the numerical results are accurate with no numerical oscillation. At last, we apply this method to simulate underwater explosion near free surface, which shows good agreement with previous result. This work is only this first step to research underwater explosion phenomenon. Cavitation and water harmer effect will be considered in future research.

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